# Welcome to the
## Multi-qubit Coherent Operations Proposers Day

| Time | Session | Presenter |
|---|---|---|
| 08:30 – 8:35 | Introductory Remarks | Dr. Michael Mandelberg<br>MQCO Program Manager |
| 08:35 – 9:00 | IARPA Overview | Dr. Lisa Porter<br>IARPA Director |
| 9:00 – 10:15 | MQCO Overview | Dr. Michael Mandelberg<br>MQCO Program Manager |
| 10:15 – 10:30 | Contracting Overview | Dr. TR Govindan<br>ARO Contracting Officer |
| 10:30 – 11:00 | Break | |
| 11:00 – 12:15 | Proposers' Presentations | (government not present) |
| 12:15 – 12:30 | Administrative Remarks | Dr. Michael Mandelberg<br>MQCO Program Manager |
| 12:30 – 1:45 | Lunch Break – On your own<br>(Gov't Representatives Depart) | |
| 1:45 – 4:00 | Posters and Teaming Discussions | |

# Multi-Qubit Coherent Operations (MQCO) Proposers Day
# IARPA-BAA-09-06 Overview

Dr. Michael Mandelberg

Program Manager

June 3, 2009

# *Disclaimer*

❑ **This presentation is provided solely for information and planning purposes.**

❑ **The Proposers' Day Conference does not constitute a formal solicitation for proposals or proposal abstracts.**

❑ **Nothing said at Proposer's Day changes the requirements set forth in a BAA.**

❑ **Any conflict between what is said at Proposer's Day and what is in a BAA will be resolved in favor of the BAA.**

# *Goals of Proposer's Day*

❑ **Familiarize participants with IARPA's interest in Multi-Qubit Coherent Operations – Please provide feedback, this is your chance to alter the course of events.**

❑ **Foster discussion of synergistic capabilities among potential program participants, AKA teaming. Take a chance, someone might have a missing piece of your puzzle.**

❑No White Papers

❑Proposals due 45 days after BAA is published.

❑Having a Proposers' Day gives you a little more time to think about your ideas.

# *Today's Topics*

- ❑ **Program Overview – background and overall goals**

- ❑ **Program Metrics and Milestones – specific tasks**

- ❑ **Award Information – how is the program structured**

- ❑ **Eligibility Information – who can propose**

- ❑ **Proposal Review Information – how your proposal is evaluated**

- ❑ **Question periods will be sprinkled throughout**

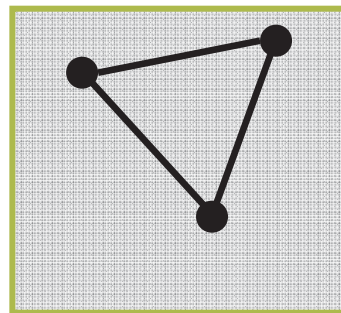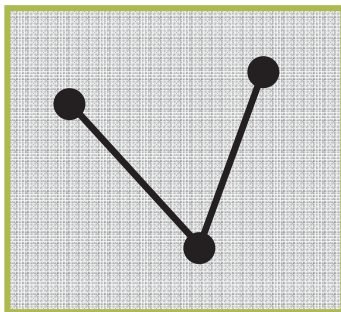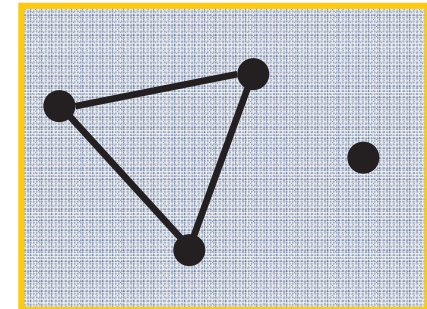MQCO Program Proposers Day

# PROGRAM OVERVIEW

**Multi-qubit System – a set of qubits for which:**

❑ **All qubits can be initialized**

❑ **A subset of at least three of the qubits:**

➢ **Can be operated on by single qubit gates**

➢ **Can be measured and read out**

➢ **Form a connected graph where the nodes are the qubits, and the edges are 2-qubit entangling gates.**

**This is connected**

**This is connected**

**This is not connected**

# *Steady progress has been made in the basic understanding and operation of qubit technologies*

**1994** ❑ **Shor's algorithm discovered (Shor)**

**1995** ❑ **Quantum error correction schemes proposed (Shor and others)**

**Several different quantum systems proposed**

**1995** ❑ **Quantum computation with cold trapped ions (Cirac and Zoller)**

**1997** ❑ **Superconducting charge qubits (Schnirman *et al*)**

**1998** ❑ **Quantum computation with quantum dots (Loss and DiVincenzo)**

**1999** ❑ **Quantum logic gates in optical lattices (Brennen *et al*)**

❑ **Entanglement of atoms via cold controlled collisions (Jaksch *et al*)**

❑ **Josephson junction quantum bits w/controllable coupling (Makhlin)**

**2001** ❑ **Linear optics quantum computing (Knill *et al*)**

**Rapid growth in research on these qubit technologies**

❑ **Total number of publications more than 10,000 over the past 10 years (according to INSPEC database).**

## *The time is ripe to focus attention on systems with multiple qubits*

- ❑ Building on these robust ideas, several research groups have demonstrated <u>considerable control</u> of qubits using these fundamentally different physical implementations.

- ❑ Progress at accomplishing two-qubit interactions in a <u>well controlled</u> manner has also been demonstrated, with some qubit implementations providing sufficient control to implement high quality <u>two</u> qubit entangling gates; even a few <u>three</u> and <u>four</u> qubit algorithms have been performed.

- ❑ Following this avenue toward the goal of fault tolerant quantum computing, most research to-date has focused on improving the fidelity of physical systems composed of a small number of qubits.

- ❑ At times the progress has seemed slow, yet a careful assessment of the last ten years makes it apparent that the degree of control over one- and two-qubit systems has improved <u>substantially</u>.

# *Program Goals*

- ❑ **Goal:**
  - ➢ **Building upon the scientific progress of the last ten years: define, explore, and address the challenges of <u>fabricating and operating multiple qubits simultaneously, and in close proximity.</u>**
- ❑ **Challenges (degree of difficulty varies by qubit):**
  - ➢ *Fabrication/yield (circuit width)* **– In other words, difficulty creating a system with more qubits.**
    - • **Photons (sources)**
    - • **QDs (growth in regular arrays)**
    - • **Optical lattices (deterministic loading)**
  - ➢ *"Crosstalk" (circuit depth and width)* **– This is essentially all the new noise that comes from a more complex environment, having more "stuff" around.**
    - • **JJs (electrical crosstalk)**
    - • **Neutrals/ions (optical crosstalk)**
    - • **Anything in a cavity (spectral crowding)**
  - ➢ *Control (circuit width)* **– As more qubits are added, challenges arise in the complexity of the control systems.**
    - • **Hardware (*e.g.* wiring density, lines into dilution refrigerators)**
    - • **Software (e.g. automating complex operations to reduce overhead and improve experimental throughput)**
    - • **Validating operations when the Hilbert space gets big**
  - ➢ *Footprint* **(circuit width) – Including supporting equipment/infrastructure, how big is the multi-qubit system?**
    - • **Bulk optics**
    - • **Dilution refrigerators**
    - • **Racks of pulse generators**
    - • **Large laser systems**

# *Program Plan (High level, details below)*

- ❑ **Three (3) phases over five (5) years:**
  - ➤ Each phase will build upon specific technical goals that must be achieved to proceed to the next, culminating in a final set of algorithm demonstrations.
- ❑ **Phase 1 high level goals (24 months): Preliminary multi-qubit capability**
  - ➤ Design, fabricate and test multi-qubit system
  - ➤ Develop draft Test Plan for Phase 2 goals
- ❑ **Phase 2 high level goals (12 months): Multi-qubit behavior**
  - ➤ Redesign and fabricate multi-qubit system
  - ➤ Quantify the behavior of the multi-qubit system
- ❑ **Phase 3 high level goals (24 months): Multi-qubit demonstrations**
  - ➤ Redesign and fabricate a multi-qubit system with sufficient capability to execute quantum information processing tasks
  - ➤ Demonstrate a quantitatively improved multi-qubit system (over Phase 2) and use it to successfully perform two distinct multi-qubit quantum information processing tasks

**MQCO Program Proposers Day**

# Questions?

# Technology Choice

❑ **Qubit Technology Requirements:**

➢ **The choice of qubit to use for the multi-qubit system is open, but the chosen technology should have already been used to demonstrate high quality single qubit control**

➢ **This technology should have demonstrated a scalable two-qubit universal gate, or**

➢ **This technology should have demonstrated high quality two-qubit coupling with a clear path toward a two-qubit scalable universal gate with imminent experimental validation, or**

➢ **This technology should have a clearly described two-qubit controlled interaction capability with a sound theoretical basis for which experimental validation is imminent.**

➢ **The chosen approach must have long term promise as a quantum computing technology.**

❑ **Note:**

➢ **The team should have demonstrated experience with qubit operations so that they can progress quickly toward the program goals.**

➢ **All technologies must increase the number of processor qubits to no fewer than three, and more is better.**

# Five promising qubit technologies

❑ **This presentation will highlight five promising qubit technologies. These represent likely future directions. This discussion is not a limitation on what ought to be proposed.**

❑ **Near state-of-the-art results and foreseeable technical hurdles for the five most promising candidate technologies for multi-qubit quantum systems are shown.**

❑ **While proposals for other qubit choices are possible, the reported results in the scientific literature indicate that the above mentioned five technologies have the necessary baseline capabilities that are amenable to meeting the program goals.**

❑ **It is expected that technical proposals will compare the proposer's capabilities with state-of-the-art benchmarks and address the foreseeable technical hurdles.**

# Progress of multi-qubit experimental demonstrations
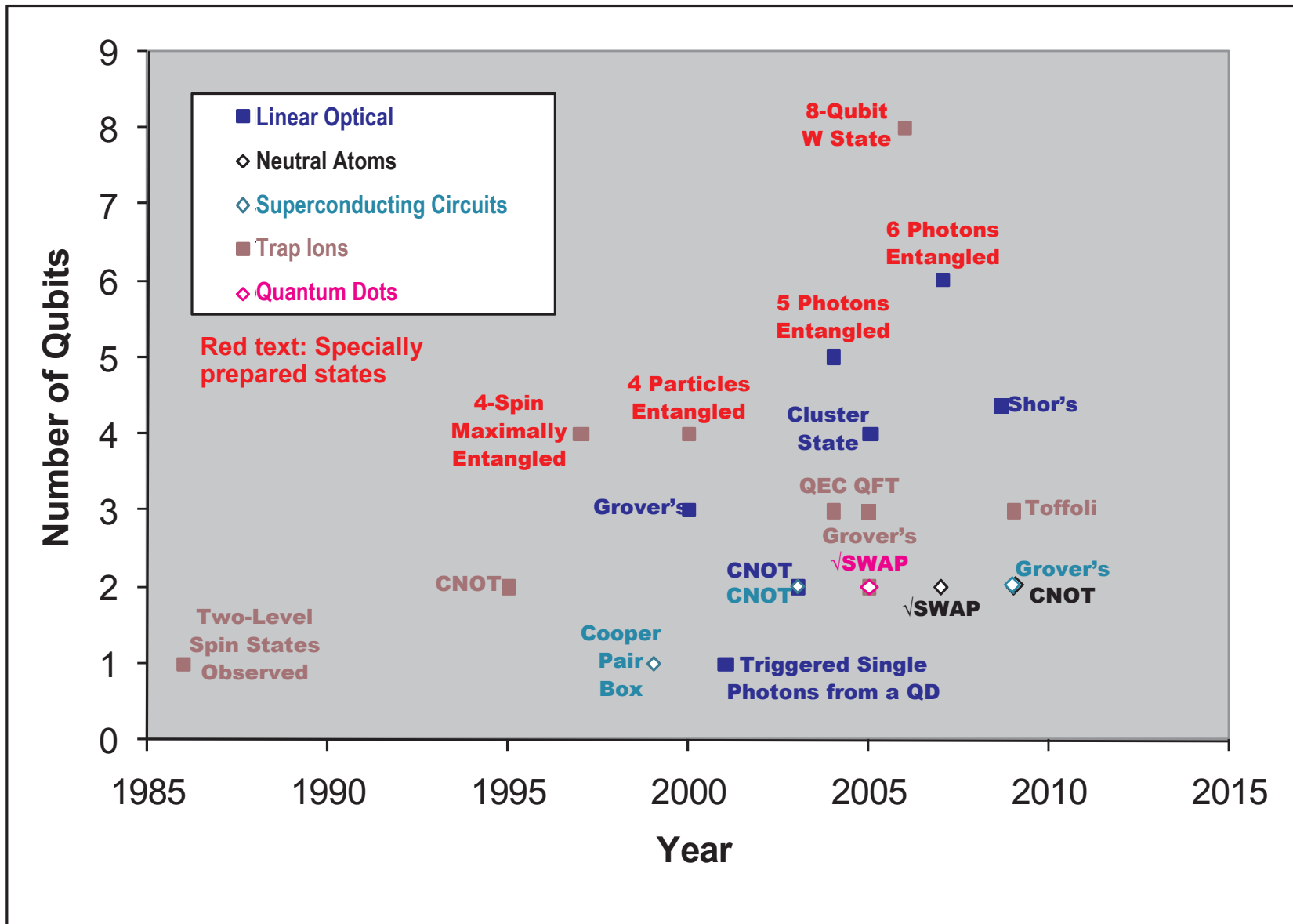
# Semiconductor quantum dot status and challenges

| Some Key Results |
|---|
| ▪ **Spin state preparation (several)** |
| ▪ **Single qubit coherent manipulation (several)** |
| ▪ **Electrical control of electron spin (Delft)** |
| ▪ **2QD Single-shot readout (Harvard)** |

**Some Key Challenges**

- Two-qubit gates
- Cross-talk from control lines
- Control hardware
- Transporting quantum information
- Leveraging standard industrial processes for few electron devices
- Wiring density/number of feed-throughs into dilution refrigerator
- Low noise electronics
- Fabrication yield
- Qubit variability

# Ion trap status and challenges

| Some Key Results |
|---|
| ▪ QFT (NIST) |
| ▪ Entanglement purification (NIST) |
| ▪ QEC (NIST) |
| ▪ Toffoli gate (Innsbruck) |

**Some Key Challenges**

- ▪ Cross-talk (scattering of resonant light)
- ▪ Ion cooling/heating
- ▪ Fast laser switching and pulse shaping
- ▪ Fabricating and operating on surface traps*
- ▪ Complicated trap structures – junctions, integrated optics, etc.
- ▪ Laser multiplexing
- ▪ Blue light generation and control
- ▪ Sympathetic cooling of many ions
- ▪ Cryogenic operation

**\* Surface traps will be required of an ion trap proposal**

# Neutral atom status and challenges

## Some Key Results

- **Multi-particle entanglement (Max Planck Institute)**

- **Massively parallel operations (NIST)**

- **Collisional √SWAP (NIST)**

- **CNOT Rydberg gate (U. Wisconsin)**

## Some Key Challenges

- **Deterministic loading**
- **Fast readout**
- **Single qubit addressing**
    - •**Laser focusing**
    - •**Beam steering**
- **Cross-talk (scattering of resonant light)**
- **Transporting quantum information**
- **Turnkey, miniaturized laser systems**
- **Two qubit gates**
- **Cooling**
- **Atom loss**

# Superconducting circuits status and challenges

## Some Key Results

- **Two-qubit gate (several)**

- **Deutsch-Josza algorithm (Yale)**

- **QND measurement (several)**

- **Two-qubit quantum state/process tomography (several)**

## Some Key Challenges

- **Cross talk from control lines and nearby qubit operations**
- **Fast single shot readout**
- **Transporting quantum information**
- **Qubit calibration and stability**
- **Wiring density/number of feed-throughs into dilution refrigerator**
- **Fabrication yield**
- **On-chip control circuitry**
- **Controllable qubit coupling**

# *Photonic circuits status and challenges*

## Some Key Results

- **2-qubit Grover's search algorithm (LANL)**
- **4-qubit cluster state (Vienna)**
- **Deutsch algorithm, four-qubit cluster state (Queen's U.)**
- **Shor's algorithm to factor 15 (Queensland)**

## Some Key Challenges

- **Deterministic single photon sources**
- **Detectors (speed, efficiency, number resolution, jitter)**
- **Integrated optics (passive/active, materials science for photons?!)\***
- **Memory/delays**
- **Entanglement with known (unwanted) DoF**

**\* Integrated optics will be required of a photonic circuit proposal**

# *Technology Choice*

➢ **Different qubit types have attained different levels of achievement. Some technologies have demonstrated coherent interactions between many qubits while others have just recently demonstrated two-qubit gates. These past achievements will not be used to judge one qubit type against another.**

➢ **Hybrid approaches are acceptable, but only if they provide a clear advantage, and this advantage is clearly articulated.**

# *Theory is a part of any complete team*

❑ **Just some examples…**

  ➢ **Design – all levels of the multi-qubit system**

  ➢ **Modeling – qubit behavior, interaction with other components, etc.**

  ➢ **Control – optimal control theory, feedback control, etc.**

  ➢ **Noise Model – predict and interpret experiment**

  ➢ **Algorithm – what would be a suitable algorithm for your number of qubits?  Be imaginative!**

  ➢ **State validation/visualization – How are we going to know what's going on with those qubits?**

  ➢ **Dynamical Decoupling – Time to put this into action.  Will require further development of the theory for realistic constraints.  Can it be used during gate operations?**

  ➢ **Decoherence Free Subspaces – If they are there, and they help, find them and use them.**

# *Additional Guidance*

❑ **Program Focus:**

> The focus of the MQCO program is to advance <u>circuit-based</u> (to include cluster state) quantum computation, specifically to address the challenges inherent to multi-qubit systems. Research into the topics of <u>quantum simulation</u>, <u>communications</u>, <u>memory</u> and <u>entanglement</u> is *not* supportive of this program *unless they explicitly enable or advance circuit-based quantum computation*.

❑ **Proposers should be aggressive yet realistic when choosing**

> - the number of qubits (circuit width)
> - the number of consecutive quantum operations (circuit depth)
> - the number of parallel quantum operations

  **for their multi-qubit systems at end of each Phase.**


❑ **Single Qubit Performance Improvement (not the primary goal):**

> While pursuing new challenges associated with multi-qubit systems, single qubit performance improvements are a natural and desirable part of the design process. However, single qubit fidelity improvement is <u>not the primary goal of this program</u>. Though single qubit improvement is an important and difficult problem, this program is designed to identify and address problems that are unique to increased qubit number and density.

# *Additional Guidance*

❑ **The submitted proposal should include a full discussion of how the program goals will be met. Technical issues that should be specifically addressed are:**

➢ **Technology chosen (type of qubit), and its anticipated coherence properties.**

➢ **Description of state-of-the-art in this technology for qubit initialization, control, and readout for one, two (or more) qubits.**

➢ **Method(s) for performing qubit gates (one- and two-qubit), and their anticipated performance – particularly fidelity and speed. Provide motivation for this choice of gate(s) along with possible alternatives. If two-qubit gates are not currently available, justification should be given as to the theoretical expectations of fidelity and speed, along with detailed plans for their imminent verification.**

➢ **Method(s) for single and multiple qubit single shot measurement and readout. Include their anticipated performance, particularly with respect to fidelity, speed, and back action.**

➢ **Method(s) for characterizing state and process fidelity for the anticipated number of qubits at the end of the program.**

# *Additional Guidance*

❑ **Proposal contents, technical issues (continued):**

➢ **Components of the anticipated multi-qubit system, their functional descriptions, and physical layout.**

➢ **Supporting technologies that will be required to accomplish the major milestones within the proposal and the availability of these supporting technologies, and a description of any work that needs to be accomplished if these supporting technologies are not currently available.**

➢ **Number of qubits that will be in the multi-qubit system at the end of each phase, along with a technical justification of these choices.**

➢ **Major technical hurdles that must be overcome to realize the final multi-qubit system, along with proposed strategies for overcoming these challenges. Special attention should be paid to anything posing difficulties with respect to:**

- **multi-qubit fabrication/yield**
- **cross-talk during multi-qubit operation**
- **multi-qubit control/validation**
- **footprint of multi-qubit system and supporting equipment.**

# *Additional Guidance*

❑ **Proposal contents, technical issues (continued):**

  ➢ **In all cases, portions of the proposed approach which clearly stand opposed to its scalability as a quantum information processor should be identified, and explanation provided as to why these difficulties do not obviate the utility of this approach.**

# *Additional Guidance*

❑ **Programmatic issues that should be discussed in the proposal:**

➢ **Team's current technical capabilities.**

➢ **Key resources needed (not currently available to the team), to include capital equipment and special expertise (teaming will likely play an essential role in providing special expertise). The risk in acquiring these key resources, and mitigation strategies, should be indicated as well.**

➢ **A teaming plan along with the roles and responsibilities of each member of the research team.**

➢ **End of Phase and some intermediate milestones are set, but it is expected that other intermediate milestones that are on the critical path of the proposed approach will be offered.**

➢ **A schedule of all milestones including a clearly charted description of the various risk mitigation strategies that will be undertaken to achieve the important (particularly end of phase) milestones.**

# *Out of Scope*

□ **Some technologies are not suitable for this program:**

  ➢ **Early research (theoretical or experimental) that has not yet demonstrated quality control over a single qubit.**

  ➢ **Classically distributed quantum computing (also known as Type-II quantum processing systems)**

  ➢ **Adiabatic quantum computing**

  ➢ **Technologies for which there is a well known barrier to scaling up to useful quantum information processing systems.**

  ➢ **Creation of quantum states that are not useful for algorithm demonstration unless otherwise specifically requested**

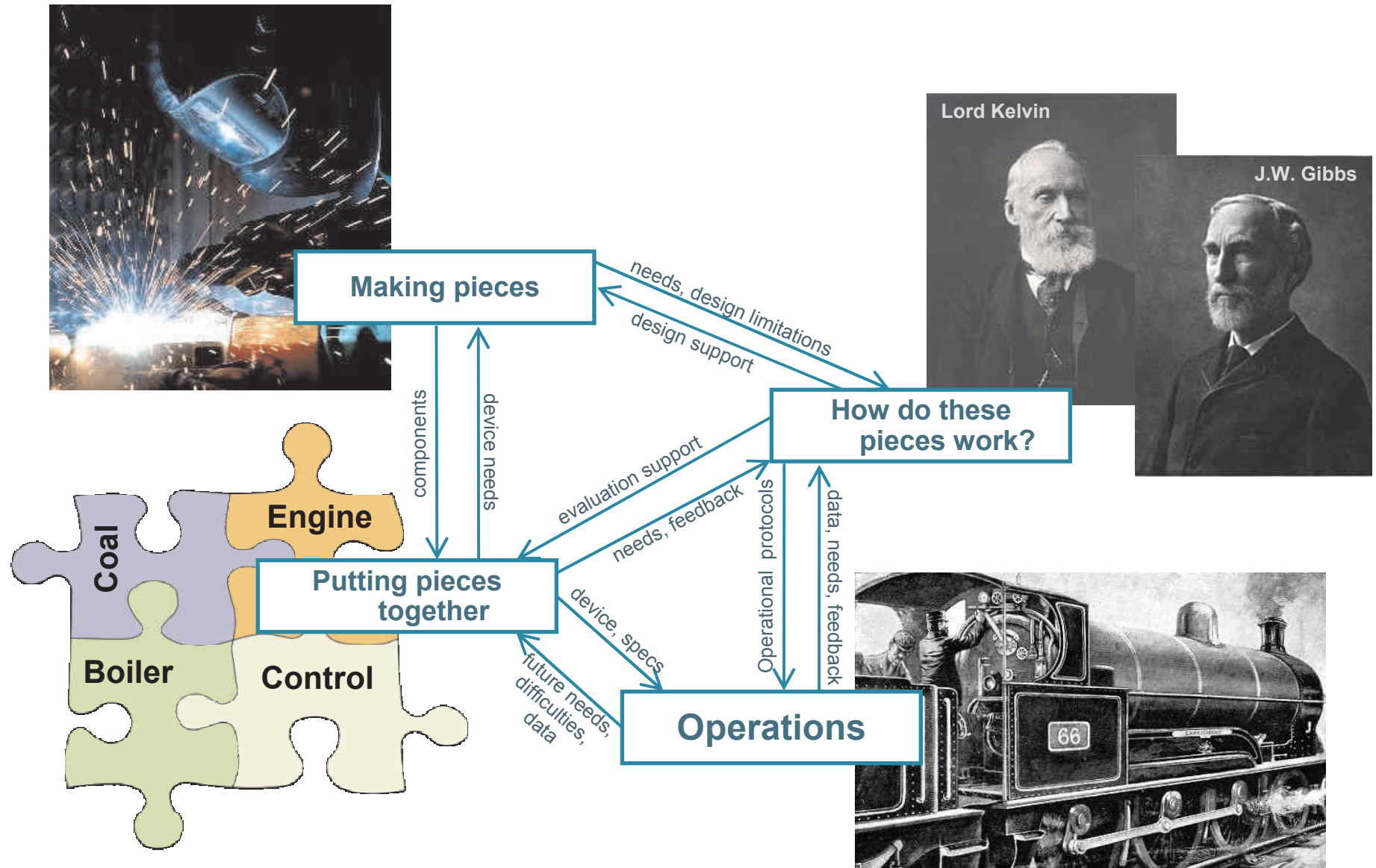  ➢ **Proposals that are incomplete with respect to the program goals**

# *Teaming*

- ❑ **Because of the many challenges in designing, fabricating, and testing a multi-qubit device, both depth and diversity will be beneficial for overcoming these challenges.**
  - ➢ **Experimental throughput – experiments are difficult and time consuming. Consider all that you will need to do, all the ideas you will need to test.**
    - • **Parallel operations** *e.g.* **perfecting 2-qubit gate while at same time testing readout or improving other qubit structures. This may require multiple dilution refrigerators. Make sure you have enough people, both experiment and theory, and widgets to do the job**
    - • **Sufficient resources to follow critical path while still exploring alternatives – risk mitigation**
  - ➢ **Completeness – teams should not lack any capability necessary for success,** *e.g.* **should not rely upon results from the community at large, or some enabling technology to be developed elsewhere.**
  - ➢ **Tightly knit teams**
    - • **Clear, strong, management, single point of contact**
    - • **No loose confederations**
    - • **Each team member should be contributing significantly to the program goals. Explain why each member is important,** *i.e.* **if you didn't have them, what wouldn't get done?**
    - • **No teaming for teaming's sake.**
- ❑ **Remember, you may be very accomplished, but can you do it all?**

Making pieces

How do these pieces work?

Putting pieces together

Operations

Coal

Engine

Boiler

Control

Lord Kelvin

J.W. Gibbs

66

needs, design limitations

design support

components

device needs

evaluation support

needs, feedback

device, specs

future needs, difficulties, data

Operational protocols

data, needs, feedback

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# Questions?

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# Program Metrics & Milestones

# Progress Indicators

❑ **Program Milestones and Metrics:**

➢ **Evaluate the effectiveness of proposed solutions in achieving the stated program objectives.**

➢ **Determine whether satisfactory progress is being made to warrant continued funding of the program.**

➢ **Bound the scope of effort, while affording maximum flexibility, creativity, and innovation in proposing solutions to the stated problems.**

➢ **Proposer may suggest that one or more milestones are not suitable. If so, the reasoning should be fully explained, and an alternate milestone suggested as appropriate. Such deletions must be approved.**

➢ **Proposer may suggest additional milestones.**

# *Test Conditions and Standards*

- ❑ **All tests at end of phase will be performed on the same multi-qubit system.**

- ❑ **All data reporting must adhere to standard statistical tests that include quantification of significance, error bars, or other statistical measures.**

- ❑ **It is assumed that quantum state/operation fidelity will be assessed using quantum tomography, unless proposer suggests effective alternative.**

# *Interim Milestone Scheduling*

❑ **The proposal should address all three phases. The proposal should talk about technical and scheduling details of all of the milestones for Phase 1, both interim and final, including interim milestones the BAA recommends, and ones the proposer suggests. The same holds for Phases 2 and 3, except the following are not due until the preceding phase:**

➤ **the schedule of interim milestones**

➤ **the definition of proposer suggested interim milestones**

❑ **The BAA will not suggest the schedule for interim milestones. There are some dependencies among them, but they are extremely variable by qubit type, and, to a degree, within a qubit type depending on some detailed technical choices. The BAA will stress that these milestones shouldn't be left to the end of the phase.**

# Phase 1 Milestones and Metrics

- ❑ **Phase 1 Theme: Combine many components to demonstrate a multi-qubit system that is beyond current state of the art, specifically with respect to number of qubits (within that particular qubit technology).**

- ❑ **To encourage realization of a general-purpose quantum logic processor, all the tests will be performed on a single system.**

- ❑ **At the end of Phase 1, a Test Report will be submitted to demonstrate the capability of the multi-qubit system to perform quantum operations.**

- ❑ **End of Phase results will be reviewed based upon the successful implementation of the Phase 1 Test Plan and the submission of a draft Test Plan for Phase 2. Fidelity of operations is *not* a critical evaluation criterion.**

# *Phase 1 Milestones and Metrics*

| Phase 1 Milestones | Suggested Metric |
|---|---|
| 1. Design for multi-qubit system for Phase 1 Test Plan. | N/A |
| 2. Submit Test Plan for Phase 1. At a minimum it must cover items 4 - 8 of this table. | N/A |
| 3. Fabricate/implement a multi-qubit system for Phase 1 Test Plan. | N/A |
| 4. Demonstrate single qubit gates on all qubits. | Single qubit gate speed and fidelity |
| 5. Demonstrate single shot read-out on all qubits. | Measurement speed and fidelity |
| 6. Measure single qubit coherence properties on all qubits (individually). | $T_1$ and $T_2$ |
| 7. Demonstrate two-qubit gates on all qubits. | Gate speed and fidelity |
| 8. Specify how multi-qubit operations will be assessed. If other than quantum process tomography, justify that this is an adequate means. | N/A |
| 9. [Proposer suggested] | ??? |
| 10. Submit Report on result of Phase 1 testing. | N/A |
| 11. Submit draft Test Plan to meet Phase 2 milestones. | N/A |

# Phase 1 Milestones and Metrics

❑ **Proposers should submit additional <u>interim milestones</u> (in the proposal) to be achieved on the way towards the final exam at the end of 24 months. Examples of milestones are:**

➢ **First design of multi-qubit system**

➢ **First multi-qubit system fabricated**

➢ **Coherence testing on individual qubits**

➢ **….**

**These milestones should be appropriate for the specific technology and design specifications and should include scheduling information.**

❑ **End of Phase 1 requirements:**

➢ **Multi-qubit system must be a significant advance over previous state of the art in terms of number of qubits and qubit density**

➢ **Single qubit control must be demonstrated**

➢ **Two-qubit gating must be demonstrated**

➢ **Fidelity is *not* the primary goal for Phase 1, but there must be a clear path to achieving the control required to implement the Phase 2 Test Plan by the end of Phase 2**

➢ **Test plan for Phase 2 must be complete (to the extent possible given the to-be-determined Phase 2 designs)**

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# Questions?

# *Phase 2 Milestones and Metrics*

❑ **Phase 2 Theme: Identify the biggest challenges to quantum coherent operations in a multi-qubit environment.  Lessons learned in this Phase will be implemented for progress during Phase 3.**

❑ **As with Phase 1, tests must be performed on a single multi-qubit system.**

❑ **At the end of Phase 2, the redesigned multi-qubit system will have been tested in accordance with the approved Test Plan (updated) submitted at the end of Phase 1.  A Test Report will be submitted giving detailed results about the multi-qubit performance.**

❑ **End of Phase results will be reviewed based upon the successful implementation of the Phase 2 Test Plan and submission of two distinct algorithms for the final Phase 3 demonstration.**

# Phase 2 Milestones and Metrics

| Phase 2 Milestones | Suggested Metric |
|---|---|
| 1. Design of final Phase 2 multi-qubit system | N/A |
| 2. Submit updated Test Plan for phase 2. At a minimum it must cover items 4 - 14. | N/A |
| 3. Fabricate/implement a multi-qubit system for Phase 2 Test Plan | N/A |
| 4. Initialize and calibrate all qubits from multi-qubit system of item 3. | Speed and fidelity of initialization, and lifetime of calibration |
| 5. Demonstrate and characterize one- and two-qubit gates while holding nearby qubits in various specific states. | Speed and fidelity of gated and idled qubit operation |
| 6. Demonstrate and characterize one- and two-qubit gates while performing various gate operations on nearby qubits. | Speed and fidelity of operation on all gated qubits |
| 7. Demonstrate single shot readout on all qubits while holding nearby qubits in various specific states. | Speed and fidelity of measurement and idled qubit operation |
| 8. Demonstrate single shot readout on all qubits while performing various gate operations on nearby qubits. | Speed and fidelity of measurement and gate operation |
| 9. Characterize the readout back action for items 7 and 8. | N/A |

# Phase 2 Milestones and Metrics

| Tentative Phase 2 Milestones (cont.) | Suggested Metric |
|---|---|
| 10. Demonstrate the application of a Hadamard gate to all qubits (in parallel or serially). | Speed and fidelity of operation |
| 11. Demonstrate and evaluate dynamical decoupling, during gate operation if possible. | Operation fidelity |
| 12. Transport quantum information beyond nearest neighbor and quantify the impact of this operation on coherence of transported information. | Operation fidelity |
| 13. Demonstrate maximum entanglement of arbitrary pairs of qubits | Operation fidelity |
| 14. Demonstrate parallel operations of one- and two-qubit gates. | Operation fidelity and circuit width |
| 15. [Proposer suggested] | ??? |
| 16. Submit Report on result of Phase 2 testing | N/A |
| 17. Specify the two information processing tasks that will be performed to meet Phase 3 requirements. They should have significant circuit width, depth, multi-qubit entanglement, and nearby parallel gate operations. | N/A |

# Phase 2 Milestones and Metrics

❑ **Proposers should submit additional interim milestones to be achieved during Phase 2. These may be a part of the Report submitted at the end of Phase 1, and do not need to be a part of the proposal. These milestones should be appropriate for the specific technology and design specifications and should include detailed scheduling information.**

❑ **End of Phase 2 requirements**

  ➢ **Successful implementation of redesigned multi-qubit system.**

  ➢ **Performance of the approved Phase 2 Test Plan.**

  ➢ **Phase 2 Report should define challenges, both previously known and newly discovered, to increasing circuit width and depth, paying particular attention to: fabrication/yield, cross talk, control, and footprint.**

  ➢ **Phase 2 Report should, where possible, compare results to similar experiments performed on one- and two-qubit systems.**

  ➢ **Phase 3 algorithms must be submitted and approved.**

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# Questions?

# Phase 3 Milestones and Metrics

❑ **Phase 3 Theme: Design and fabricate an improved multi-qubit system based upon the lessons learned from Phase 2. Upon completion, it is expected that this improved system will demonstrate superior performance to the Phase 2 system on most aspects of the Phase 2 Test Plan.**

❑ **This Phase 3 system will be used to demonstrate two distinct quantum algorithms and complete other tasks on the approved Phase 3 Test Plan.**

  ➢ **Distinct, here, means both in terms of the operations performed, and the regions of Hilbert space explored, modulo qubit permutations.**

  ➢ **These should be composed of one- and two-qubit gates, though other gates (such as native Toffoli gates) may be used if their implementation is fully explained and justified.**

  ➢ **It is expected that both of the tasks will be aggressive in both their circuit width and depth.**

# *Phase 3 Milestones and Metrics (cont.)*

❑ **As with Phases 1 and 2, tests must be performed on a single multi-qubit system.**

❑ **Upon completion of Phase 3, teams are expected to submit a Final Report detailing Phase 3 Test results along with answers to the following questions:**

➢ **What lessons were learned?**

➢ **What would be the next design and how would it address the outstanding issues?**

➢ **Among the new challenges found, identify those for which there is (currently) no practical solution and among these, identify those for which a near to mid-term practical solution is not foreseen.**

# *Phase 3 Milestones and Metrics*

| Tentative Phase 3 Milestones | Suggested Metric |
|---|---|
| 1. Design of final Phase 3 multi-qubit system | N/A |
| 2. Submit Test Plan for Phase 3. At a minimum it must cover items 4 - 10. | N/A |
| 3. Fabricate/implement a multi-qubit system for Phase 3 Test Plan | N/A |
| 4. Apply Phase 2 Test Plan to Phase 3 multi-qubit system. It should have improved performance in almost all areas. | See Phase 2 milestones |
| 5. Demonstrate Bell's inequality violation between pairs of physically separated qubits on the multi-qubit system. | Bell Inequality |
| 6. Implement two distinct multi-qubit quantum information processing tasks. | Speed and operation fidelity performed at each time step |
| 7. Characterize the noise and make a quantitative comparison with error models. Place special emphasis on correlated (multi-qubit) errors. | N/A |
| 8. Quantify the error budget within the multi-qubit system, identifying physical source of each contribution. | N/A |
| 9. Demonstrate a clocked sequence of parallel gates that includes two-qubit gates. This could be done in the algorithm demonstrations of item 6. | Operation fidelity performed at each time step |

# Phase 3 Milestones and Metrics

| Tentative Phase 3 Milestones (cont.) | Suggested Metric |
|---|---|
| 10. Characterize multi-qubit performance stability, during a single run and between algorithm runs. | Proposer suggested |
| 11. [Proposer suggested] | ??? |
| 12. Submit Final Report on result of Phase 3 testing and future directions | None |

# *Phase 3 Milestones and Metrics*

❑ **Proposers should submit additional interim milestones to be achieved during Phase 3. These may be a part of the Report submitted at the end of Phase 2, and do not need to be a part of the proposal. These milestones should be appropriate for the specific technology and design specifications and should include detailed scheduling information.**

# *Technical Reporting Requirements*

- ❑ **Monthly Technical Report – just an email, not onerous, what's going on?**
- ❑ **Monthly Financial Report – form will be provided**
- ❑ **Program Review – annual, August of every year, conference format**
- ❑ **Site visit – annual, including phase kick-off and review meetings**
- ❑ **Web conference – annual**
- ❑ **Test Plans – written submission, as per milestones**
- ❑ **Test Reports – submitted at end of each Phase**

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# Questions?

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# Award Information

# *Award Plan*

- ❑ **5-year Program starting FY 1Q 2010**
  - ➢ **Phase 1 - Base Period - 24 months (to begin November 2009)**
  - ➢ **Phase 2 - Option Period - 12 months**
  - ➢ **Phase 3 - Option Period - 24 months**

- ❑ **Criteria for moving to each Phase: success against previous Phase's Test Plan**

- ❑ **Multiple awards anticipated, depending upon**
  - ➢ **quality of the proposals received**
  - ➢ **availability of funds**

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# Eligibility Information

# *Eligibility Information*

- ❑ **Collaborative efforts/teaming strongly encouraged**
  - ➢ **Content, communications, networking, and team formation -responsibility of proposers**
- ❑ **Foreign organizations and/or individuals may participate**
  - ➢ **Must comply with Non-Disclosure Agreements, Security Regulations, Export Control Laws, etc, as appropriate**
- ❑ **Other Government Agencies, Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), and any organizations that have a special relationship with the Government, including access to privileged and/or proprietary information, or access to Government equipment or real property, are not eligible to submit proposals under this BAA or participate as team members under proposals submitted by eligible entities.**
- ❑ **If you wish to utilize any resources from these organizations, please let me know ASAP. If IARPA determines that the resources are unique and do not exist in the private sector, IARPA will attempt to work directly with that organization to arrange for that capability to be made available to all program participants who might benefit.**

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# Proposal Review Information

# *Evaluation Criteria*

❑ **Evaluation criteria in descending order of importance are:**

- ➤ **Overall Scientific and Technical Merit**
- ➤ **Effectiveness of Proposed Work Plan**
- ➤ **Relevance to IARPA Mission and MQCO Program Goals**
- ➤ **Relevant Experience and Expertise**
- ➤ **Cost Realism**

❑ **All responsive proposals will be evaluated by a board of qualified government reviewers. Each proposal will be evaluated by at least three reviewers.**

# *Point of Contact*

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# Thank You!
# Any Final Questions?

**Look for an MQCO BAA sometime in the next few weeks**

http://www.iarpa.gov/solicitations.html